U.S. Department of ENERGY

Methane Mitigation Technologies Multi-Year Program Plan

January 2025

List of Acronyms

Bcf/d	Billion Cubic Feet per Day
BLM	Bureau of Land Management
BSEE	Bureau of Safety and Environmental Enforcement
BOEM	Bureau of Ocean Energy Management
CO_2	Carbon Dioxide
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
FECM	Office of Fossil Energy and Carbon Management
FOA	Funding Opportunity Announcements
FY	Fiscal Year
GHG	Greenhouse Gas
GHGI	U.S. Greenhouse Gas Inventory
IRA	Inflation Reduction Act
LDAR	Leak Detection and Repair
LDAQ	Leak Detection and Quantification
LNG	Liquified Natural Gas
Mcf	Thousand Cubic Feet
MERP	Methane Emissions Reduction Program
METEC	Methane Emissions Technology Evaluation Center
MMRV	Measurement, Monitoring, Reporting, and Verifying
$MMTCO_2e$	Million Metric Ton CO_2 Equivalent
MYPP	Multi-Year Program Plan
NAS	National Academy of Sciences
NETL	National Energy Technology Laboratory
NREL	National Renewable Energy Laboratory
P&A	Plugging and Abandonment
PAH	Polycyclic Aromatic Hydrocarbons
PHMSA	Pipeline and Hazardous Materials Safety Administration
PNNL	Pacific Northwest National Laboratory
RNG	Renewable Natural Gas
R&D	Research and Development
RSG	Responsibly Sourced Gas
SLED/M	Smart Leak Detection-Methane
UOW	Undocumented Orphaned Well
VOC	Volatile Organic Compound

Table of Contents

List of Figures

1. Overview

1.1 Introduction and Background

The O&G system consists of more than 2 million producing, abandoned, or repurposed oil and natural gas wells, more than 2 million miles of pipeline, over 10,000 processing plants, compressor stations, and gathering stations. Across the natural gas production, processing, and transmission systems, EPA estimates that around 3.2 BCF was emitted in 2022. This equates to approximately $1 billion in annual revenue.

A leading challenge associated with mitigating methane emissions from the oil and natural gas value chain is the complexity of these systems and the magnitude of the number of individual operating components widely distributed across all corners of the country.

The Methane Mitigation Technologies (MMT) Multi-Year Program Plan (MYPP) is focused directly on improving the reliability and resiliency of, and reducing methane emissions across, the entire oil and natural gas infrastructure. The MMT Program aims to: (1) develop technologies in advanced pipeline materials, pipeline sensors and systems, pipeline data management and computational tools, in-pipe inspection and repair technologies, and compressor and engine methane slip mitigation technologies; (2) develop advanced modular natural gas conversion technologies, capable of being deployed near wellheads, natural gas processing facilities, and transportation infrastructure, for the purpose of beneficially utilizing otherwise flared or stranded natural gas; (3) develop advanced methane sensor technologies to detect and quantify methane emissions from production fields, pipelines, infrastructure equipment, storage facilities, and abandoned wells; (4) develop and validate methane emissions detection and measuring technologies to accelerate adoption of the most accurate and cost-effective methods, including superior and even transformational technologies that have yet to gain a significant market share; and, (5) develop an industry and academia-supported data center that will leverage data analytics, including artificial intelligence, to support quantification and validation of multi-scale emissions data across the oil and natural gas value chain.

1.2 Alignment with Administration and Congressional Priorities

The MMT Program is directly aligned with broader DOE strategy and Congressional direction received through annual funding appropriations, emerging regulatory developments (e.g., EPA, DOT PHMSA), the current state of technology development, and the perspectives of the scientific research community. This alignment is described in the following sub-sections.

DOE Strategy

The Division of Methane Mitigation Technologies' R&D program aligns with the DOE strategy to "develop energy technologies that increase the affordability of domestic energy resources." Affordable energy is central to modern life. DOE will focus on early-stage research and development (R&D) through pre-commercial technology validation to make energy more affordable for American families.

DOE is committed to the development of energy technologies that make best use of our abundant domestic energy resources. We will accelerate development by investing in one of America's greatest strengths, its unlimited capacity for innovation, enabling safe and prudent production of these domestic resources to make energy more affordable, while leveraging American competitive advantages to seize market opportunities for manufacturing.

Congressional Language

Congressional direction with regard to methane mitigation and monitoring research is evident from the Fiscal Year (FY)2025 Congressional budget guidance.

FY2025 Senate guidance for FECM DMMT: S. Rept. 118-205 - ENERGY AND WATER DEVELOPMENT APPROPRIATIONS BILL, 2025 | Congress.gov | Library of Congress

"The recommendation includes $58,000,000 for Methane Mitigation Technologies, which includes activities previously funded through Emissions Mitigation from Midstream Infrastructure and Emissions Quantification from Natural Gas Infrastructure. The Committee supports advanced methane mitigation solutions and novel sensor technologies that allow for continuous and remote monitoring of emissions for upstream, midstream, and distribution gas infrastructure. Further, the Committee remains supportive of investment in smart pipeline sensors and controls, internal pipeline inspection and repair, and composite and advanced material science technologies."

"The Department is encouraged to collaborate with external stakeholders in making use of commercial assets to monitor methane emissions from satellites and other methane emissions detection technologies to isolate the source of emissions at the individual facility level and to explore technologies, including in coordination with public-private partnerships, that promote innovative approaches, such as detection technologies in support of reducing methane gas emissions. The recommendation includes up to $5,000,000 for advanced observational technologies, as validated in peer-reviewed publications, to globally identify and mitigate methane and volatile organic compound emissions from existing operations assisting worldwide partners and governments deploy targeted reduction measures. Further, the Department is directed to brief the Committee within 180 days of enactment of this act on the progress for this work."

"The Committee recognizes that the several million orphaned (unplugged and abandoned) wells in the United States are a significant source of fugitive methane emissions. A rapid, cost-effective method is needed for suppressing these emissions before the wells can be properly plugged and abandoned. In fiscal year 2024, the Committee recommended an additional $6,000,000 to provide for university-led research and development of biofilm based reactive barrier technologies that can significantly reduce atmospheric methane emissions from orphaned wells. The Committee encourages the Department to move forward on that funding and update the Committee accordingly."

“The Committee recognizes the advancements of United States manufacturers of Vapor Recovery Units and Devices [VRUs] in their development of specialized computing systems and data streams in the management of emissions. The Committee supports ongoing efforts by private industry in technologies, advancements, and concepts to capture and utilize fugitive volatile organic compounds and methane gas at the wellhead or individual facility level. The Department is instructed to collaborate with external shareholders in making use of commercially available VRUs to capture methane emissions utilizing the latest technologies to isolate the source of emissions at the wellhead or individual facility level and to explore improved technologies, including in coordination with public-private partnerships, that promote innovative approaches that also include detection and monitoring technologies in support of identifying and reducing methane gas emissions. The Committee directs the Department to support these efforts, including research, assessment, and deployment to support activities that easily demonstrate VRUs to be implementable, maintainable, and a safe integrated methane reduction solution.”

“The Department is encouraged to collaborate with external stakeholders in making use of commercially available technology solutions to monitor methane emissions and isolate sources of emissions at the individual facility level or finer scales; and to explore, advance, and scale-up new and innovative methane emission detection and quantification solutions that further support reduction of methane emissions, including coordination with public-private partnerships.”

“The Committee is encouraged by what the Department is doing through Advanced Scientific Computing Research [ASCR] at the Office of Science to better understand machine learning and uncertainty quantification for complex systems and directs the Department to provide up to $10,000,000 to set up a similar program in the Office of Fossil Energy and Carbon Management to further evaluate advanced data collection, storage, and integration. Additionally, this program can direct the development of new data science, statistical modeling, and uncertainty quantification approaches to improve the interpretation and understanding of methane emissions data.”

FY2025 House guidance for FECM DMMT : H. Rept. 118-580 - ENERGY AND WATER DEVELOPMENT AND RELATED AGENCIES APPROPRIATIONS BILL, 2025 | Congress.gov | Library of Congress

“The Department is directed to support research and development activities to assess the feasibility of utilizing vapor recovery units as a methane reduction solution, including the use of technologies to isolate the source of emissions at the wellhead or individual facility level. The Department is encouraged to explore improved technologies, including in coordination with public-private partnerships. “

“Within available funds, the Committee provides $10,000,000 to establish a university-based methane emissions monitoring data analytics center. The center should be a consortium of academia, national labs, and industry focused on data integration, analytics, processing, and visualization from methane monitoring sensors to provide easily accessible and actionable information to industry and other stakeholders to better mitigate, predict, and prevent methane leaks from natural gas production.”

“The Department is encouraged to support activities to develop and demonstrate an easily implementable, maintainable, and low-cost integrated methane monitoring platform. The Committee includes up to $6,000,000 for university-led research and development of biofilm based reactive barrier technologies that can significantly reduce atmospheric methane emissions from orphaned wells.”

Industry and Science Community Perspectives

The 2019 National Petroleum Council study, titled "Dynamic Delivery, Americas Evolving Oil and Natural Gas Transportation Infrastructure" made 41 recommendations, where 10 recommendations are related to technology research and to be led by the Department of Energy.[1] These include:

- Technologies to better identify, locate, and quantify methane emissions
- Combustion engines that will enhance combustion efficiency and reduce methane slip while not increasing criteria pollutant emissions
- Develop efficient and cost-effective methods for directly measuring methane in the exhaust.
- Remote sensing technologies and geospatial analytics, specifically to improve data accessibility and costs
- New pipeline and repair coating systems
- Improve stability of TMCP steel's physical properties that are exposed to high heat conditions above 500°F
- Inspection technologies that would allow operators to inspect installed steel and composite sleeves without the need for excavation and field inspection
- Most effective measures of integrity of casing and cement as well as casing and cement logging improvements
- Well inspection technologies that can improve integrity logging, and reduce the frequency of tubing removals
- A nationwide research effort to improve accuracy, reliability, and applicability of anthropogenic methane emission estimates, from the individual facility to the regional/national scale

The 2022 National Academy of Sciences study, titled "Greenhouse Gas Emissions Information for Decision Making: A Framework Going Forward, made the following recommendations:[2]

- Greenhouse gas emissions information (e.g., observations, data analysis, activity data, emission factors) development at more granular temporal and spatial scales with source-level detail should be accelerated to meet the rapidly increasing needs of cities, states, and provinces for managing their emissions.
- The accuracy and representativeness of all underlying data used to estimate greenhouse gas emissions (e.g., emission factors, activity data) should be further improved.
- Greenhouse gas emissions estimation research efforts should urgently transition to operational capabilities in collaboration with institutions to maintain and ensure longevity.
- Greenhouse gas emissions data collection, modeling, and information development should be designed and implemented to enable a fuller integration and "hybridization" of information and approaches.

Government Performance Results Targets

Several targets have been set by the research program in addition to those highlighted in the previous section for supporting effective resource development and reducing emissions from waste or stranded natural gas. For example, by 2028, a targeted goal is to accelerate development of technologies to dramatically reduce or eliminate the use of flares at the wellhead through gas processing and/or conversion to other sustainable chemicals and low-carbon marketable products, with a target of reducing average methane emissions from formerly flared gas by 90%.

Interagency Collaborative Efforts

EPA's Methane Emissions Reduction Program (MERP), created by the Inflation Reduction Act (IRA), provides $1.55 billion in funding, including financial and technical assistance to reduce methane and other greenhouse gas (GHG) emissions from the oil and natural gas sector with the co-benefit of reducing non-GHG emissions such as volatile organic compounds and hazardous air pollutants. Complementary to DOE-funded efforts, MERP is focused on facilitating the implementation of commercially available, off-the-shelf methane mitigation approaches. These efforts include applying existing plugging technologies to marginal conventional wells, and zero-bleed pneumatic controllers to natural gas transportation systems. DOE's FECM, through the National Energy Technology Laboratory (NETL), is collaborating with EPA to help implement this program expeditiously during FY2023 through FY2028.

1.3 Overarching Goals and Desired Benefits of RD&D Investments

Near-Term Actions (FY2025)

The MMT Program's FY2025 R&D plan is designed to accelerate the development, scale-up, field validation, acceptance, and implementation of impactful solutions by 2030. The Program's objectives are to:

- Research, assessment, and deployment to demonstrate that vapor recovery units (VRUs) are implementable, maintainable, and a safe integrated methane reduction solution.
- Develop strategies for eliminating natural gas flaring and accelerate technology solutions to support sustainable chemical conversion pathways.
- Establish methane emissions data analytics center for methane emissions data related to oil and natural gas production, transport, storage, and refining/processing. Leverage data center to support region specific approaches for emissions monitoring and technology validation.
- Expand the Methane Emissions Testing Center to other U.S. Regions: Improve measurement and quantification of methane emissions from the upstream and midstream oil and natural gas value chains through the development and validation of advanced characterization and monitoring technologies, including remote sensing, aerial monitoring tools, and local point-source sensors. These consortia will also seek to develop collaborative best practices for measurement, quantification, and data utilization.
- Improve capabilities for detecting and monitoring methane emissions across the oil and natural gas production, processing, transportation, and storage sectors, as well as the renewable natural gas (RNG) production sector (e.g., through the development of improved sensors, low-cost leak indicators, and more accurate remote sensing methods).

- Develop more accurate and representative methane emissions factors for specific equipment components across the U.S.
- Through rigorous basin scale field assessments, reconcile the differences between atmospheric (also referred to as "top-down" estimates through satellite, towers, and aerial remote sensing approaches) and engineered (also referred to as "bottom-up" estimates based upon equipment counts coupled with emission factors) emissions estimates for all hydrocarbon fuel sectors.
- Develop more effective, lower-cost retrofits of equipment components prone to leaks or chronic emissions (e.g., pneumatic valve controllers, compressor seals and packing, natural gas fired engines, and distribution lines).
- Continue the development of the Integrated Methane Measurement and Monitoring Characterization Platform (IM3CP). A low-cost, efficient, accurate, implementable, and maintainable system to enable early detection, notification, and real-time quantification of methane emissions across the oil and natural gas supply chain.
- Develop cost-effective methods for locating orphaned oil and natural gas wells and quantifying their emissions, in order to prioritize their management and plugging.

Mid-Term Actions (FY26-FY30)

The MMT Program's mid-term R&D plan includes a focus on development of a multi-scale measurement, monitoring, reporting, and verifying (MMRV) system, an increased focus on natural gas storage and liquified natural gas (LNG) emissions, the cost-effective plugging and abandonment of undocumented orphaned wells, and an expansion of research to include the application of methane mitigation technologies developed for the oil and natural gas value chain to other industrial sources where methane leakage can occur. The Program's objectives will be to:

- Employ advanced technology methods for detecting, quantifying, and mitigating methane emissions from oil & gas towards active and abandoned coal mines (e.g., gob well-venting control systems, mine mouth capture systems, and mine air ventilation systems).
- Adapt land-based emissions sensing and mitigation technologies to maritime LNG operations. Focus on point-source quantification and mitigation of engine-slip from shipboard generator engines.
- Reduce the environmental impact and emissions of undocumented orphaned wells by characterizing emissions and impacts, developing cost-effective plugging and abandonment technologies, and field-testing materials, sensors, and processes.
- Improve natural gas storage integrity by improving characterization of the long-term effects of natural gas storage operations on wellbore material integrity and developing advanced subsurface monitoring methods, improved wellbore integrity monitoring, and remediation tools.
- Continue operation of up to three pilot-scale systems designed to eliminate associated natural gas flaring and develop further disruptive approaches to utilize waste and stranded natural gas through conversion into economically viable fuels and chemicals.

Long-Term Plan (FY30+)

Long-term plans for the MMT Program include an increased focus on:

- **Natural Gas Distribution and End-Use**: Continue to mitigate methane emissions from natural gas distribution systems through low-cost retrofits and remediation solutions. Develop and employ advanced materials to support increased hydrogen concentration in industrial and residential systems.
- **Natural Gas Processing and Crude Oil Refining**: Lessen the emissions footprint associated with natural gas processing and crude oil refining through improvements in combustion efficiency, improved resiliency in surface storage vessels, and multi-scale, real-time, continuous emissions monitoring.
- **Sustainable Chemicals from Stranded Gas**: Continue to refine and expand the footprint of technologies for generating sustainable chemicals synthesized from stranded natural gas via modular or small/medium-scale centralized facilities. Continue to develop resilient pipeline transport capacity to support economic viability of sustainable approaches. Support end-use industrial technology requirements for fuel switching.
- **Renewable Natural Gas**: Improve biochemical reaction efficiency for RNG synthesis. Leverage field laboratory concepts to test and validate RNG "lifecycle" viability at scale in a near-commercial environment, while fully quantifying emissions footprint.
- **Abandoned Coal Mine Emissions Quantification and Mitigation**: Develop novel technologies to remotely assess methane emissions from abandoned coal mines and mine portals, along with new, low-cost materials and procedures for effective plugging and sealing these emissions sources.
- **Quantifying and Mitigating Methane Leakage from Other Industrial Sources**: Pursue research, validation, and broad deployment of disruptive, scalable, low-cost technology concepts for effective quantification and mitigation of methane leakage for other industrial sector point source emissions such as coal mines, landfills, and industrial plants.

Program Snapshot

As of January 6, 2025, the MMT Program includes 41 active projects that are distributed across the following eleven categories: (1) Advanced Sensors, (2) Compressors, Engines, and Generators, (3) Detection and Field Trials, (4) Integrated Methane Monitoring, (5) Natural Gas Conversion and Conditioning, (6) Natural Gas Demand Response, (7) Partnerships, (8) Pipeline Resiliency, (9) Fundamental Research, (10) Methane Emissions Reduction Program, and (11) Undocumented Orphaned Wells.

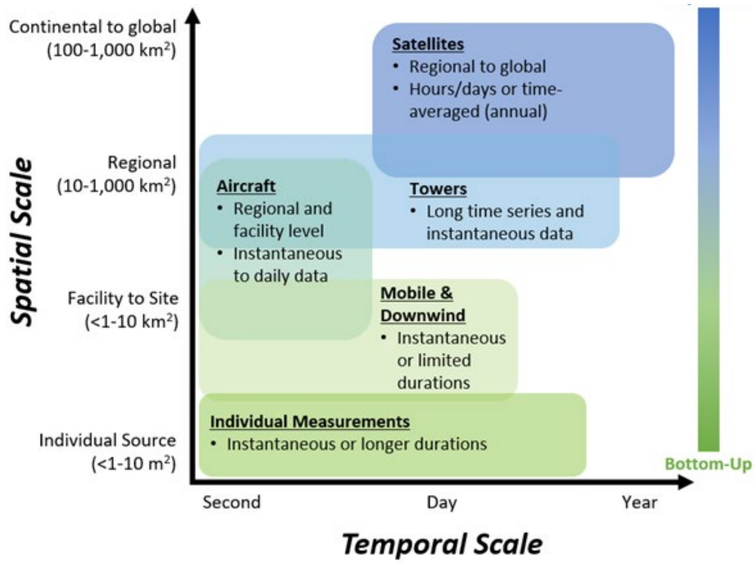
2. Technical Plan – Methane Mitigation Technologies Program

2.1 Methane Measurement and Quantification Description and Goals

DOE and FECM are focused on the development of new technologies for monitoring and measurement of methane leakage across the entire natural gas and oil value chain, and on the development of an integrated approach to reconciling conflicting assessments of the primary sources of methane emissions to the atmosphere. Only by quickly and accurately identifying the location and rate of methane leakage within the oil and natural gas supply chain can mitigation and repair efforts be validated and prioritized.

There is debate about the overall accuracy of current EPA GHGI methane emission estimates, which are developed through a "bottom up" estimation approach.[3] This approach estimates methane emissions from emitting events (e.g., liquids unloading) or specific equipment components, using associated emissions factors combined with the number of devices and the frequency of activities. The accuracy of these estimates depends on the accuracy of the equipment counts, characterization of active and legacy equipment, methane emission factors, and modeling approaches. Another methane quantification approach is commonly referred to as a "top-down" approach since it based off sensing equipment attached to stationary equipment, crewed and uncrewed aircraft, or satellites to estimate methane emissions of methane occurring across a given area based on concentrations and atmospheric conditions (Figure 1). The top-down methods used to characterize methane emissions have significant uncertainty in accuracy due to the measurements typically being limited to a short time period that may not correspond with the timing of irregular emission events, as well as typically having measurements taken during midday when the atmosphere is well mixed. Other challenges include obscuring dust, wind, weather, and competing sources of methane emissions, both natural and anthropogenic. In some cases, top-down estimates of emissions and bottom-up inventories have significantly differed, leading to the need for reexamination of estimates from both approaches. Reconciling the differences between these two approaches is fundamental to understanding not only the true impact of methane emissions on climate change[4], but also to identifying how best to focus emissions mitigation efforts.

Figure 1. Spatial and Temporal Scale of Top-Down and Bottom-Up Quantification Technologies



FECM's approach regarding the detection, quantification, and measurement of methane leakage is to develop direct and indirect measurement sensor technologies, as well as intermittent and continuous monitoring technologies to enable the collection of reliable data, support innovative research, and improve analytics that support both quantification and emission inventories relevant to the natural gas supply chain. The primary focus of FECM efforts has been on advanced leak detection technologies (e.g., remote, real-time, and autonomous detection) and the field testing and validation of developed technologies in relevant conditions and at relevant sites (e.g., projects such as Methane Emissions Technology Evaluation Center [METEC]). Accordingly, the Methane Measurement and Quantification sub-program element includes five R&D subtopic areas that are collectively focused on addressing the four objectives outlined in the above rationale: (1) Multi-Scale Emission Source Identification and Characterization, (2) Detection and Measurement Technologies, (3) Analytical Process Development, (4) Integrated Methane Monitoring Technologies, and (5) Pilot and Field Demonstrations.

Multi-Scale Emission Source Identification and Characterization

Efficient detection and quantification of methane leakage over large spatial areas (e.g., hundreds of square miles, state, and regional levels) and over a range of time frames (e.g., intermittent and continuous) is a required capability necessary to ensure efficient transport and delivery of natural gas to end users. Demonstrating the effectiveness and accuracy of surface-based methane emissions detection and quantification networks at field- to regional-scale will support the integration of top-down and bottom-up leakage analysis to optimize the natural gas supply chain and ensure that leakage repair operations are appropriate.

Further, FECM is focusing on the demonstration of methane measurement technologies and analysis methods for quantifying methane leakage along the natural gas supply chain with a focus on basin-specific requirements. DOE efforts will be aimed at improving emission factors for components and equipment that are most prevalent and that are responsible for emitting the majority of methane along the natural gas supply chain (e.g., compressors, engines, and gathering and boosting stations). Improvements will be supported by developing a deeper understanding of basin specific leakage measurement, quantification, and emission factors through field testing and validation.

Detection and Measurement Technologies

Over the past decade, there has been significant progress made on surface-based (e.g., ground, tower) and aerial technologies (e.g., drone, aircraft) for detecting and quantifying methane leakage. These include static monitors, hand-held sensing and measurement devices, vehicle-based detection sensors, autonomous unmanned aerial vehicles, and aircraft. However, many of the surface-based, point-source technologies suffer from limitations associated with their inability to quickly assess large areas, while aerial vehicles require further development and field testing to improve quantification accuracy. There is a need for continuous, surface-based and aerial gridded monitoring (noted by a NAS study and others) of methane emissions that can quickly detect and identify chronic and acute leakage sources (e.g., intermittent super-emitters) so that they can be effectively repaired and mitigated as soon as possible. DOE will continue to support the development of measurement and quantification technologies that can be deployed for real-time, remote, and continuous monitoring, which can also be scaled-up to achieve basin-wide or regional coverage to support broad identification and characterization of leakage sources and inform repair operations.

With regard to future advanced technology development, leakage measurement and quantification technologies that reduce atmospheric and other types of interference, such as clouds, wind, and dust, would enable more effective methane emission quantification from low-earth orbit satellites and improve the ability to measure and quantify methane leakage from offshore platforms. Similarly, DOE will support efforts that enable methane leakage detection and quantification continuously in varying weather patterns, as well as in low-light or no-light conditions.

Analytical Process Development

As advanced methane sensing technologies continue to be developed, the volume of data collected across the oil and natural gas supply chain related to leakage rate, volume, location, and impacts that affect infrastructure resiliency, and security requires a substantive toolset for data normalization, synthesis, and analysis.

The use of analytical tools like machine learning, artificial intelligence, and analytical validation methods, such as life cycle analysis, provide important insights on supply chain optimization and better understanding of the environmental considerations associated with resource production through distribution to end users.

DOE will establish and maintain a university-led data analytics center focused on leveraging advanced analytical techniques and computing capabilities to further clarify methane leakage impacts on multiple scales to help ensure efficient quantification and mitigation efforts across the oil and natural gas value chain.

As the state of science surrounding data collection related to methane leakage continues to advance and datasets become more complex, DOE will further development of analytical validation tools supporting important knowledge gaps associated with comparison of observed data and modeled emissions factors, validation of equipment maintenance cycles to optimize operations and maintenance scheduling, and certification requirements for export of liquified natural gas to countries in Europe and east Asia. A recent report released by NETL provided key information on the lifecycle analysis of natural gas extraction and power generation.

Integrated Methane Monitoring Technologies

Detecting and quantifying methane leaks early, before they become chronic emissions sources, is a crucial aspect of methane mitigation efforts. Early detection would likely enable operators to drastically reduce the environmental impact of super emitters that are caused by malfunctions or human error. Also, understanding the nature of chronic background emissions from collections of smaller point sources will enable operators to focus efforts to improve performance.

There is a need to support the monitoring, measurement, and mitigation of methane emissions within a low cost, efficient Integrated Methane Monitoring and Measurement Characterization Program (IM3CP) that will enable early detection and potentially also quantification of emissions along the natural gas supply chain. Such a platform will require integration of ground-based, atmospheric-based (aerial, satellite), and bridge technologies that would enable effective, accurate, and transparent detection, and quantification of methane-emissions along the oil and natural gas supply chain. Because developing an understanding of the ideal approach to designing and constructing such a platform is the first step, in the near-term, DOE will support efforts to develop a prototype of an IM^3CP that will incorporate surface level sensors, autonomous, low-cost optical methane sensors and imagers on unmanned aerial systems, the integration of methane emissions data acquired from geospatial satellites, and new multidimensional data modeling and predictive capabilities using machine learning tools. Future efforts will include field testing and validation of prototype IM^3CPs. Once developed, the platform would support broad-scale methane emissions reduction and provide critical insight into the causes of super emitters and how to reduce their frequency and impact. Similarly, the platform could assist in the selection of appropriate monitoring and sensing technologies based on a technologies probability of detection of varying emission rates.

Pilot And Field Demonstrations

DOE's efforts to advance technology development rely on pilot testing and field demonstrations to validate methane detection and monitoring systems, accelerate their deployment, and build acceptance among early adopters. Accordingly, field pilots and demonstrations will become important parts of the R&D portfolio as detection, measurement, and integrated monitoring systems reach an appropriate level of development.

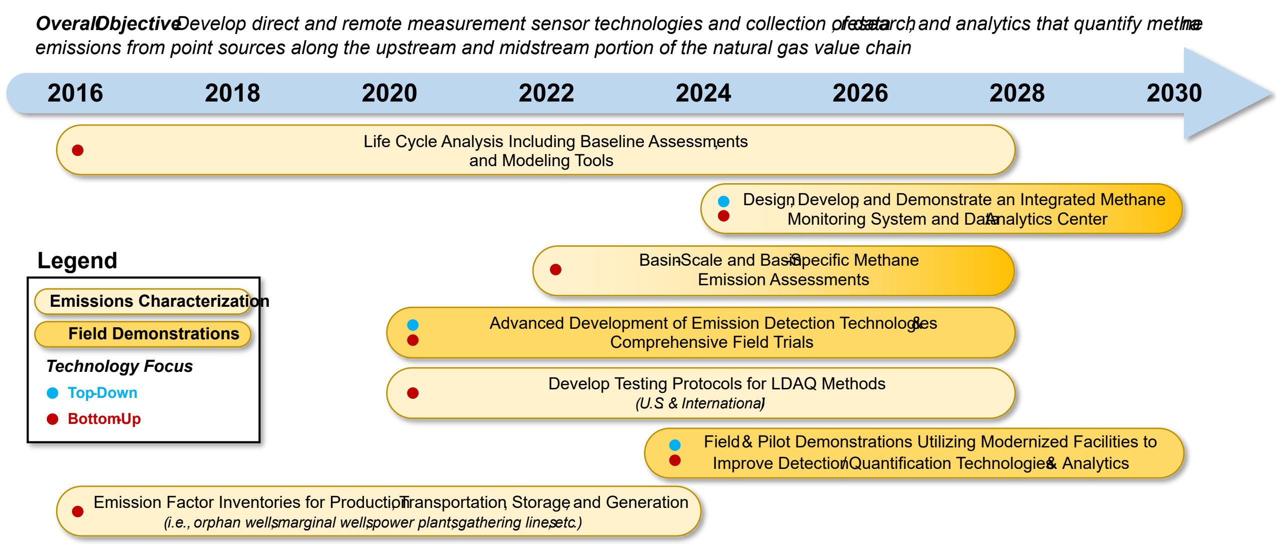
Current Research

Current technology development within the Methane Measurement and Quantification research area includes efforts to improve real-time, autonomous monitoring systems at a variety of scales to better characterize methane emissions from oil and natural gas production, transport, storage, and refining operations. Efforts also include multi-scale, basin specific field validation projects to better quantify methane emissions through a variety of ground-based, stationary, and aerial monitoring platforms, and reconciliation between "top-down" direct methane emissions measurements and "bottom-up" equipment-specific emissions inventories for improved evaluation of the environmental impact of oil and natural gas production.

TIMELINE

Figure 2 below illustrates the timing of the Methane Measurement and Quantification sub-program R&D areas over the 2016 to 2030 time period.

Figure 2. Research Timeline – Methane Measurement and Quantification



Five-Year Plan (FY25-FY29)

Future DOE-funded R&D efforts regarding methane quantification will be based on the above rationale and are connected or intertwined to a large degree through their objectives. The following descriptions provide details about efforts that will be pursued:

- **Reconciling Top-Down and Bottom-Up Emissions**: To better reconcile the differences in methane emissions that are calculated by top-down and bottom-up approaches, DOE is currently funding research to better characterize bottom-up determined emission factors of specific equipment, such as storage tanks. Future efforts will expand bottom-up analytical approaches to other equipment, such as compressor station equipment, gas engines, liquids unloading events, and other major categories of potential methane leakage. Similarly, DOE expects to support efforts to improve top-down emission quantification by developing and improving aerial and low-earth orbit satellite methane quantification technologies. DOE's focus will likely be in developing technologies that improve quantification by reducing atmospheric interference and allow quantification in low-light or no-light conditions. Efforts in advancing top-down and bottom-up technologies will ultimately culminate in the integration of a methane mitigation platform that utilizes machine learning or advanced data analytics to correlate and quantify the data that is collected.

- **Advanced Detection Technologies**: DOE has historically supported efforts to develop advanced methane detection technologies, such as the Smart Leak Detection-Methane (SLED/M) autonomous drone, remote methane sensors for pipelines and compressors, and multi-functional distributed fiber optics. These technologies were and are aimed at improving methane detection in real-time, as well as remotely to better inform methane mitigation and emission inventories. The goal of advancing detection technologies is to accelerate development and commercialization.
- **Methane Emissions Technology Evaluation Center**: Current efforts include supporting METEC, a field testing and validation center, which is operated by Colorado State University. The facility was designed to mimic relevant oil and natural gas operations by utilizing actual equipment and by engineering leaks of a known magnitude for quantification technologies to detect and quantify. The expansion and enhancement of METEC's facility will include upgrading the testing facility to replicate what is typically utilized at modern production facilities. Also included will be an increase in leak detection and quantification (LDAQ) controlled testing capabilities, LDAQ analytics, and integrated "hythane" (methane [CH_4]/hydrogen [H_2]) testing. Additionally, collaborations will be undertaken that include EPA, Bureau of Safety and Environmental Enforcement (BSEE) and Bureau of Ocean Energy Management (BOEM) of the U.S. Department of the Interior (DOI) for R&D related to offshore and satellite technologies.
- **Field Validation of Detection Technologies**: In addition to the planned METEC expansion, other future efforts will be aimed at developing continuous, real-time, and remote quantification technologies that can be integrated within an IM^{3}CP, as well as technologies that can reduce atmospheric interference and operate in low-light and no-light conditions.
- **Integrated Methane Measurement, Monitoring, and Characterization Platforms**: DOE is currently funding efforts to design an IM^{3}CP design through projects selected in February 2023, which aim to combine disparate data streams, quantification technologies, and quantification methods into a seamless system that can provide real-time information about methane emissions within a designated region. The effort includes a multi-scale approach that will combine surface-based, tower-based, aerial, and low-earth orbit technologies. Future efforts will expand upon this work by advancing the IM^{3}CP design into a prototype to be field tested and validated. Ultimately, the design and prototype will be leveraged to create a reliable IM^{3}CP that can be utilized by industry and regulators to monitor methane emissions on a scalable basis, depending on the users' needs.

2.2 Methane Mitigation Description and Goals

To positively impact resiliency, reliability, and efficiency across the U.S. oil and natural gas supply chain, DOE has three sub-topic areas within the Methane Mitigation research sub-program. DOE is focusing on developing advanced infrastructure components and technologies related to oil and natural gas production, processing, transport, and storage to support efficient upgrading and repair. To support effective resource utilization and reduce emissions from flaring of natural gas, DOE is focusing on modularizing or intensifying processes for stranded and underutilized natural gas conversion. A third sub-topic area is focused on undocumented orphaned wells, including technologies to effectively identify, characterize, and plug these potential sources of environmental and financial concerns.

DOE's approach regarding methane mitigation is to accelerate the preliminary development, validation, and pre-commercial application of cost-effective technologies that can advance mitigation capabilities across the oil and natural gas value chain. Estimated methane emissions from point sources along the oil and natural gas supply chain are compiled by EPA. The total emissions related to the natural gas supply chain in 2022 were estimated to be ~220 $MMTCO_2e$. Production of oil and natural gas account for the largest volume of measured or estimated emissions at ~129 MMTCO2e in 2022, while transmission and storage are the second largest volume of emissions at ~40 $MMTCO_2e$, and Processing is the third largest volume of emissions at ~15 $MMTCO_2e$.

Within the production sector, the identified sources of emissions are pneumatic controllers (33%), gas engines (15%), compressors (11%), equipment leaks (9%), tanks (8%), produced water (5%), pneumatic pumps (4%) and other (15%). Within the transmission and storage sector the identified sources of emissions are compressors (40%), gas engines (15%), station venting (12%), pipeline venting (9%), metering and regulating stations (7%), and other (6%). Within the processing sector, the identified sources of emissions are gas engines (65%), compressors (15%), blowdowns (9%), flares (5%), and other (6%). In each sector there are sources identified as other, but these individual sources are not identified by EPA. Gas engines and compressors (reciprocating and centrifugal) are present as major emissions sources in each sector and account for ~35.1 $MMTCO_2e$ (16%) and 32.4 $MMTCO_2e$ (15%) of total emissions across the production, transmission and storage, and processing sectors, respectively.

In 2022, the EPA methane emissions estimate from abandoned wells was equivalent to 8.5 $MMTCO_2e$. Current estimates suggest that methane emission rates for undocumented orphaned wells (UOWs) are highly variable, with >90% of the total methane emissions coming from 10% of the UOW total population. FECM has determined that this legacy emission source should be addressed by characterizing aspects of UOWs, such as their wellbore condition, by collaborating with other agencies to develop best management practices, and by developing low-cost effective plugging technologies.

Research Approach

To ensure the effective use of our Nation's vast natural gas reserves, including stranded or underutilized natural gas, and protecting the environment, DOE is supporting advancements in modular, flexible, and adaptable technologies related to natural gas processing and conversion at well sites, as well as improved ultra-high destruction efficiency flares for when flaring natural gas is unavoidable. The development of these technologies will support and enable new economically viable and environmentally sustainable options for upstream oil and gas operations. As these concepts progress, continued support will be needed to further advance the technologies to pre-commercial validation and field demonstration opportunities.

Going forward, DOE's rationale for methane mitigation R&D is based upon several basic observations and assumptions:

- While methane emissions resulting from equipment malfunctions or improper operations can and do occur, these problems are generally mitigated through manufacturer-driven product improvement efforts and/or enhanced operator training, rather than new technology development (the primary mission of FECM research), hence the program's focus on developing new technologies that can replace or improve the performance of existing equipment or practices.

- Technologies currently exist in the marketplace for directly mitigating many of the methane emission point sources that occur as part of the operational design of oil and natural gas handling equipment used in hydrocarbon production/processing (e.g., pneumatic controllers), however the relatively high cost of implementing these low-emission or no-emission technologies, particularly at legacy or marginal production and processing locations, means that emissions continue, therefore the focus on cost-effective retrofit solutions.
- Industry reaction to market forces (e.g., interest in and moves toward Natural Gas Certification) may drive more rapid adoption of existing methane mitigation technologies. FECM continues to monitor industry trends, as well as their cumulative influence on the rate of operator deployments of zero-emission or low-emission equipment and will modify the focus and intensity of its mitigation R&D program, as appropriate.
- Underutilized point source methane emissions, such as the well head flaring of associated gas, can be significantly reduced if operators implement modular technologies to process the gas and direct it to a sales line, or through novel catalytic chemical conversion to marketable carbon products or other sustainable chemicals. In cases where these modular solutions are not implemented by choice or due to technical infeasibility and a natural gas flare is unavoidable, FECM believes significant methane mitigation can still be achieved through ultra-high flare performance designs and integrated sensors that will ensure flares remain lit and operate at optimal destruction efficiency to prevent uncombusted methane and other harmful chemicals from being released.

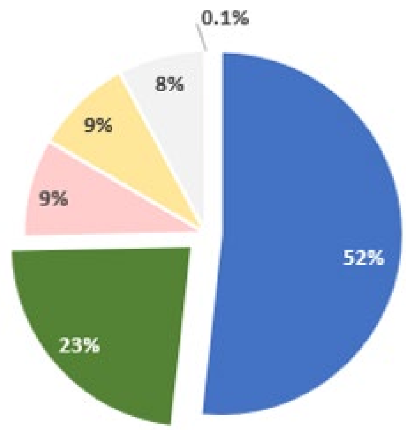
Methane Mitigation Technologies

Methane Mitigation Technologies R&D focuses on technologies that can be applied across all sectors to impact infrastructure component leakage issues, which includes retrofits or upgrades across routinely emitting devices, such as compressors and natural gas-fired engines. Within the production sector, further R&D is aimed at optimizing methane leakage from produced water and condensate storage tanks with treatment and advanced tank technologies. Additional focus within the transmission and storage sector focuses on improving pipeline integrity through inspection and repair technologies designed for existing and difficult to inspect pipelines, advanced sensors, and pipeline coatings. Research efforts within the processing sector focus on reducing natural gas flaring through conversion technologies, and on optimizing natural gas processing. Emissions sectors, as defined by EPA and that are potentially impacted by R&D supported by FECM, are represented in Figure 3.

Figure 3. EPA Methane Emissions from the Natural Gas Systems in Metric Tons of Methane

Emissions by Segment of Supply Chain

Total Emissions: ~ 173.1 $MMTCO_2e$



2022 US Methane Emissions, Natural Gas Systems Overview

Source	Percent	MMTCO2e
Production	52%	89.7
Transmission and Storage	23%	39.6
Distribution	9%	15.2
Processing	9%	15.1
Post-Meter	8%	13.4
Exploration	0.1%	0.2

Emissions by Source within the Production Sector of Supply Chain

	CH_4 Emissions (MMTCO2e)	*Value of CH_4 Lost per Year ($)*
Production Total	**89.7**	**$ 14,211,468,101***
Gas Well Workovers	0.05	$ 7,921,666
Well Pad Equipment Leaks	10.8	$ 1,711,079,771
Pneumatic Controllers	18	$ 2,851,799,619
Condensate Tanks	1.1	$ 174,276,643
Liquids Unloading	2.4	$ 380,239,949
Gas Engines	5.3	$ 839,696,554
G&B Stations - Station Blowdowns	0.9	$ 142,589,981
G&B Stations - Pneumatic Controllers	0.5	$ 79,216,656
G&B Station Yard Piping	2.8	$ 443,613,274
Miscellaneous Production Flaring	0.6	$ 95,059,987

Emissions by Source within the Transmission & Storage Sector of Supply Chain

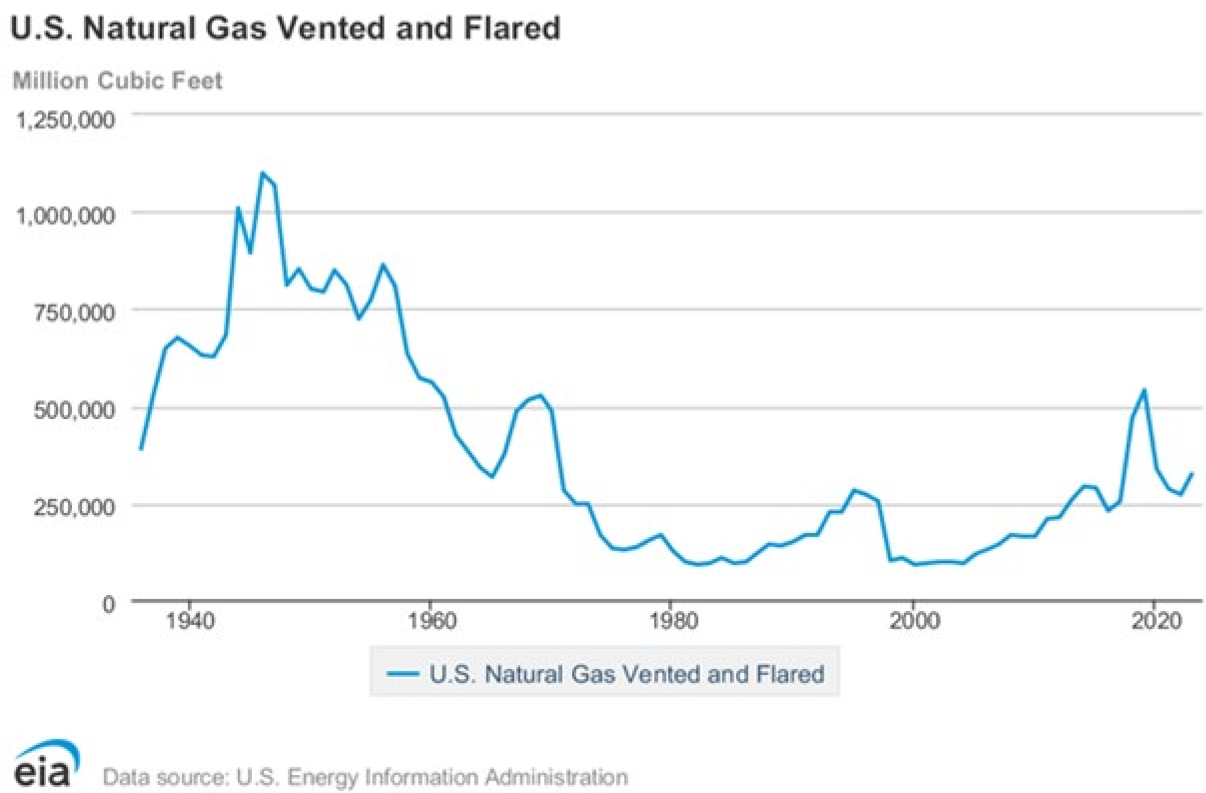
	CH_4 Emissions (MMTCO2e)	Value of CH_4 Lost per Year ($)
Transmission and Storage	**39.6**	**$224,070,015**
Transmission Compressor Station Leaks and Venting	21.5	$126,132,245
Station & Compressor Fugitive Emissions	*3.7*	*$20,299,743*
Reciprocating Compressor	*9.4*	*$51,130,391*
Centrifugal Compressor (wet seals)	*1.5*	*$8,004,685*
Centrifugal Compressor (dry seals)	*2.5*	*$13,802,710*
Dehydrator vents	0.1	$365,030
Flaring	0.01	$77,949
Pneumatic Controllers	0.9	$4,938,366
High Bleed	*0.2*	*$1,322,918*
Intermittent Bleed	*0.6*	*$3,510,407*
Low Bleed	*0.02*	*$105,041*
Station Venting	4.3	$23,235,671
Storage Wells	0.3	$1,697,455
Pipeline Venting	3.7	$20,935,695

Methane leakage from engine combustion slip, natural gas gathering and pressure boosting stations, storage tanks, and other point sources represent opportunities for research that can accelerate the development of new commercial mitigation solutions. Across all emission sectors, combustion slip from gas fueled compressor engines has been identified as a significant source of methane leakage that could be reduced through technology development, process improvement, and field pilot validation. This is also true for technologies for reducing emissions from produced fluids storage tanks, pipeline blowdowns, and a variety of other upstream and midstream natural gas venting activities. The objective of such R&D would be to accelerate development of emissions mitigation technologies that accelerate the implementation of a more resilient, reliant, and efficient oil and natural gas value chain.

Stranded And Underutilized Natural Gas Conversion

Intentional flaring and venting practices by oil and natural gas operators at well sites driven by operational, safety, or economic reasons serve as a further source of significant upstream methane emissions and poor resource utilization. Direct venting typically occurs when the volume of the flammable gas is not high enough to be considered a safety hazard, such as the emergency pressure release from compression and processing equipment, the depressurization of oil or condensate tanks without vapor recovery systems, as emissions from natural gas driven pneumatic pumps, or during liquids unloading on low-pressure gas wells. For larger volumes of natural gas during well site operations, the use of a flare is required to combust the gas rather than directly venting it to the atmosphere. This occurs for situations, such as gas influx during drilling, testing, or well completion, and during maintenance operations when gas needs to be diverted from compression and processing equipment. However, in addition to the operational and safety situations, there are also economic factors that can lead to significant volumes of natural gas going unutilized and diverted to a flare. This is the case for casinghead gas, also called associated gas, that is produced along with crude oil. When the oil price is high relative to gas prices, operators are economically motivated to burn the natural gas in flares to facilitate the more rapid production of the more valuable oil. This economic situation was exacerbated in the United States during the past decade during development of tight oil plays in areas, such as the Permian Basin in Texas and the Williston Basin in North Dakota.[5] Even when gas prices are more favorable, the lack of existing gathering, compression, and sales infrastructure for the gas can lead to prohibitive costs and time delays for operators to bring associated gas to market.[6] A plot of gas flaring across the United States, as reported to the U.S. Energy Information Administration (EIA) by various state and regional reporting agencies, highlights the increase in flaring witnessed during the last decade (Figure 4).[7]

Figure 4. Reported Natural Gas Flaring Volumes across all reporting agencies in the United States since 1936



Any natural gas that is flared is essentially wasted, with the heat content and power generation potential going unutilized, and the potential economic value of the gas to downstream markets is also lost. A study undertaken by Arizona State University estimates that $10.6 billion in revenue was lost due to flaring gas between 2012 and 2020 based on the market value of natural gas in each of those years and satellite measurements across 13 states designated by the Department of Energy as the largest contributors to flaring.[8] A 2023 economic analysis of the flaring that occurred in 2019 on federal and tribal lands estimated the economic loss at over $500 million.[9] Flaring also has negative environmental impacts, such as the release of carbon dioxide (CO_2) and soot. Even so, flaring is viewed as a preferred control mechanism to avoid methane emissions because of the lower greenhouse gas impact of CO_2. However, changes in the heat content of the feed gas or environmental factors, such as crosswinds, can extinguish flares or cause suboptimal flare performance. This results in undesired emissions, such as non-combusted methane, carbon monoxide, and sulfur dioxide and nitrous oxides. In addition, chemicals that are intended to be destroyed in the flare—such as polycyclic aromatic hydrocarbons (PAH), naphthalene, volatile organic compounds (VOCs), and formaldehyde—may not be destroyed as intended if the flare is not operating at the desired combustion level. A 2022 study published in *Science* used airborne flare sampling and unlit flare prevalence surveys in the Bakken, Eagle Ford, and Permian Basins and found that unlit flares and inefficient combustion contributed to flares effectively destroying only about 91% of emissions rather the 98% that is generally assumed by industry and government.[10] FECM is pursuing technology-based solutions to ensure that flares can adjust to changing environmental conditions and varying gas composition, such as new combustor designs, muti-gas sensor arrays, and control feedback algorithms.

DOE is also developing technologies that would give operators the ability to utilize methane without flaring and instead use new modular well site gas processing methods that route processed gas to a sales line or though transportable reactor concepts that use chemical conversion to create useful chemicals and fuels.

Undocumented Orphaned Wells

DOE further aims to improve technologies and processes for effective identification of undocumented orphaned wells; advanced sensors for the measurement, estimation, and tracking of gaseous emissions (methane, hydrogen sulfide, volatile organic compounds, and other gases) from these wells and their associated infrastructure; and the development of new characterization concepts and advanced materials for more efficient and cost-effective permanent plugging and abandonment (P&A) of such wells.

Orphaned wells are defined as wells that have no responsible operator monitoring their condition and/or that were plugged or abandoned prior to 1985 utilizing obsolete techniques.[11, 12] An undocumented orphaned well is an orphaned well that is entirely unknown to the responsible regulatory agency or a well of which the responsible agency has some evidence of existence, but its precise location and characterization requires further investigation.[13] Undocumented orphaned wells can often go undetected and uncharacterized for years or decades while potentially leaking oil, natural gas, or brine. It is estimated that there are over 92,000 orphaned wells and 310,000 to 800,000 undocumented orphaned wells among 32 oil and gas producing states.[14] Contaminants that are of particular concern with respect to groundwater and surface water include methane, arsenic, hydrogen sulfide, and benzene.[15]

The highly skewed distribution of emissions from UOWs, combined with other factors such as geographic locale and wellbore condition, creates several unique challenges to determining the best course of action to remediate a given well. In many cases, factors, such as cost and surface environment sensitivity, may limit the ability for contractors to utilize traditional well plugging and abandonment techniques. These challenges along with the sheer numbers of wells that are expected to need remediation pose a significant challenge.

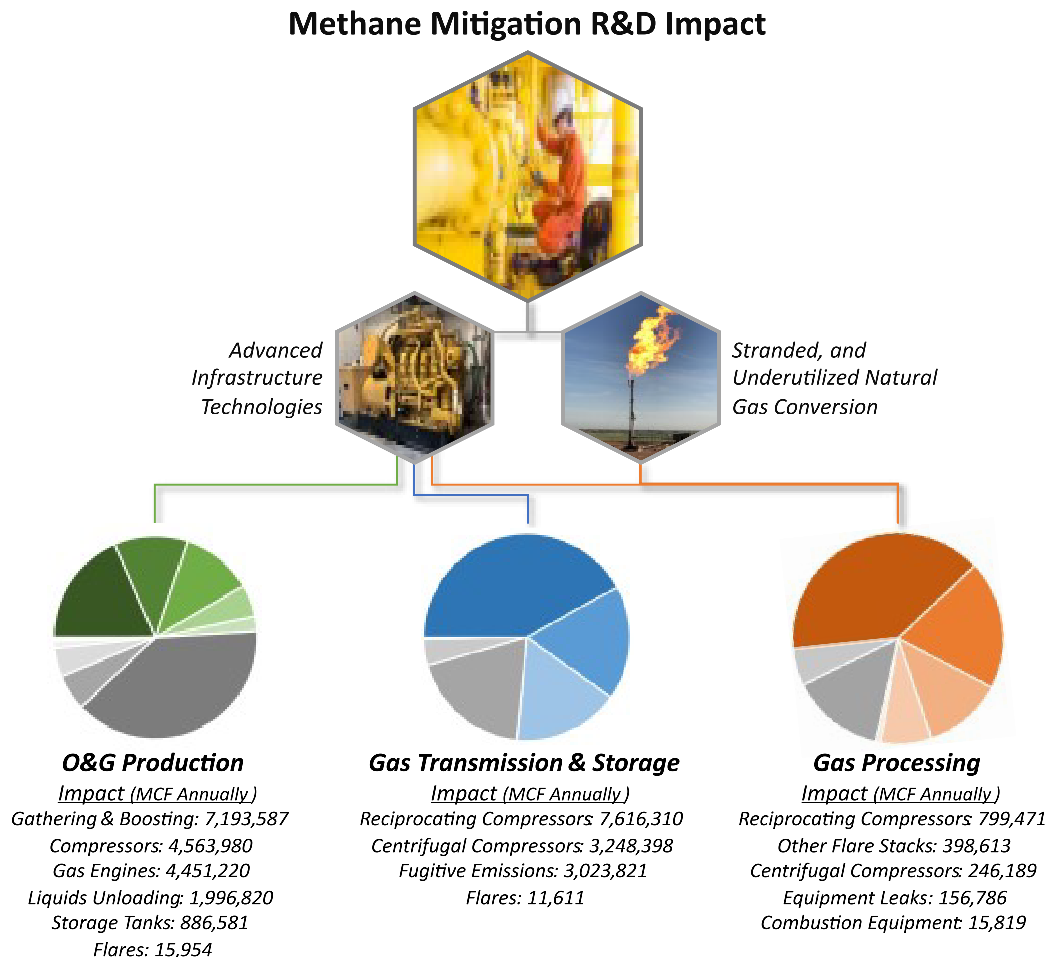
In the near-term, additional R&D is needed to mitigate methane emissions from UOWs in a cost-effective manner. Commercial remediation technologies exist for eliminating the environmental burden from UOWs. However, these technologies are not being adopted and employed as quickly as necessary, most likely due to cost, material availability, and operational factors. R&D is needed to develop alternative technologies to accelerate the deployment of remediation measures, and to advance toward commercialization of cost-effective technology options that can more efficiently characterize the condition of the UOWs and provide a range of remediation options.

Current Research

Current technology development within the Methane Mitigation sub-program area includes efforts to improve the efficiency and emissions profile of compressors and other engines along the natural gas supply chain, develop coatings and advanced materials for improving pipeline resiliency and integrity, develop advanced sensors for real-time monitoring of pipelines for leak detection and remediation, and conversion technologies to increase process efficiency and produce economically viable chemicals and other value-added products from stranded and underutilized natural gas that would be otherwise flared.

Many of the current projects have an impact in multiple sectors as they are designated by EPA as mentioned above. Project foci and their alignment with the EPA designated emission sectors are detailed in Figure 5 below (color coded to match the pie charts above).

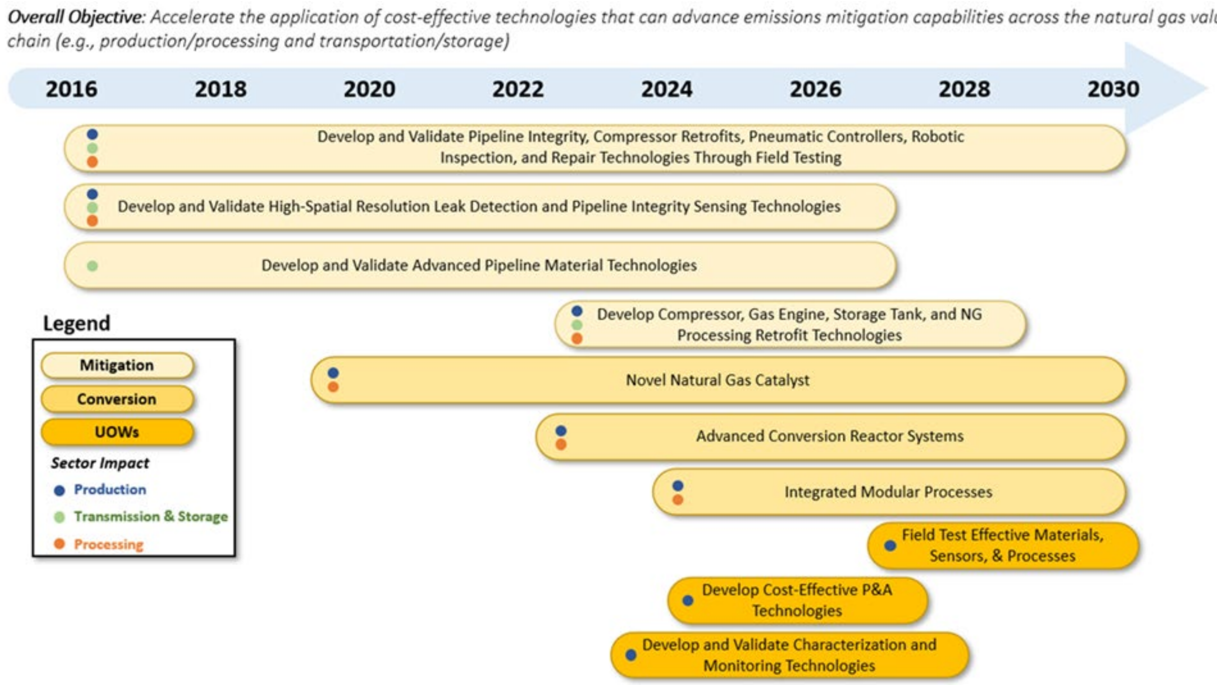
Figure 5. DOE-FECM's Methane Mitigation R&D Impact by Sector



TIMELINE

Figure 6 illustrates the timing of the Methane Mitigation research program sub-elements over the 2016 to 2030 time period.

Figure 6. Research Timeline – Methane Mitigation



Five-Year Plan (FY25-FY30)

During the near term, research will be focused on the following areas:

- **Reducing Compressor Leakage**: Both reciprocating and centrifugal gas compressors can emit methane under certain operating conditions. There are currently three projects underway focused on this issue.
- **Improving Pipeline Resiliency**: Advanced pipeline sensor systems (e.g., fiberoptic based, point source surface acoustic sensor [SAW], electrochemical) and pipeline materials (e.g., spray on liners and corrosion resistant coatings).
- **Reducing Natural Gas Engine Slip**: Natural gas-fired engines can emit uncombusted methane in their exhaust streams. Five new projects were awarded in 2023 to develop methods for reducing the volumes of methane emitted in this manner.[16]
- **Reducing Leakage from Storage Tanks**: Crude oil and condensate storage tanks at well pad locations and production facilities can be sources of methane leakage.
- **Novel Catalyst Development and Scaleup**: Projects awarded in 2019 increased understanding and identified challenges associated with multifunctional catalyst designs that facilitate multiple chemical pathways to convert methane to other products in a single step. Understanding the impact of other constituents and contaminants common in well site gas beyond laboratory mixed gases will be key to advancing these technologies and others like them for real world use. Significant challenges remain

for promising new catalysts that power autothermal reactions and have the potential to lower external energy requirements, such as deactivation by carbon build up or water produced from the combustion of hydrogen. Mitigation methods for catalyst deactivation and attrition may have to be developed and designed as additional functions of process or integrated into the catalyst itself at the nanoscale. The support structures and single atom dispersion of active sites that are likely to be required for the next generation of catalysts will also require new synthesis technologies that can not only produce the desired morphologies reliably but also reduce the overall cost to ensure economical use.

Accelerating the development of these new catalyst engineering approaches for in situ catalyst tuning, reduced attrition, and viable commercial scale up will enable the application of new chemical conversion pathways. Future research efforts will also need to support new material development for the catalysts themselves or for their integration into the reactor components. Technologies that use catalytic methane pyrolysis to synthesize high-grade carbon products will have additional challenges related to reliable catalyst separation, mitigation of metal contamination, and to ensure selectivity to specific high-value carbon nanostructures, such as carbon nanofibers, carbon nanotubes, and graphene sheets, or other carbon morphologies that can be successfully upgraded to products that can be easily differentiated from a potentially saturated market for amorphous carbon black.

- **Modular Gas Processing and Conversion R&D**: Prior and ongoing projects have accelerated the development of modular equipment design and validated methods for process intensification of conversion reactions. Continued support of these methods is needed to establish ancillary gas pre-processing needs and to field validate these methods across multiple basins, gas compositions, and production rates. A Funding Opportunity Announcement (FOA) was issued in September 2023[17] that focused on pilot-scale validation of new technologies that improve the efficiency of upstream natural gas and oil processing, separation, and conversion operations while working toward "net-zero" emission operations at the well site. The four selected projects will focus on pilot-scale field deployment and validation of efficient, cost-effective solutions that aim to eliminate routine flaring of natural gas at the well site and will be ready for pre-commercialization in real world applications.[18] These projects will engage with operators to identify a specific field location where associated gas is typically being flared to demonstrate use of the technology on-site and establish economic feasibility and pre-commercial validation. Challenges remain for new modular processes to control oxidation levels, integrate the use of any co-produced hydrogen, mitigate or beneficially use waste streams, and leverage or recycle other fractional chemical co-products formed in the reactions, such as ethylene gas that may form alongside the synthesis of aromatics. With this FOA and other activities, DOE plans to accelerate availability of new equipment, new chemical pathways, and the advancement of alternate methods of applying activation energy to enable modularity, electrification, and efficiency gains that support economic motivation for operators to avoid flaring with onsite gas processing and conversion.
- **Solid Carbon Products, Synthesized Fuels and Chemicals R&D**: DOE plans to expand options for end products that are suitable for producing at a well site and have improved transportability and widespread industrial applications with an emphasis on economic viability and sustainable production. Enabling operators to use natural gas conversion as an alternative to flaring at remote well sites without access to pipeline infrastructure will require an understanding of the impact to operators

and the economic factors across the entire value chain from on-site synthesis at the well pad, to specialized chemical and material storage and transport, and finally to responsible downstream utilization. Expanding the options for the types of sustainable chemicals that are suitable for modular synthesis ensures that operators will be able to integrate profitable chemical production tailored to onsite beneficial use or delivery to local markets. DOE plans to support this by establishing quantitative sustainability assessments over the full lifecycle of the modular technologies to support expansion of the domestic chemical economy while incorporating economically and environmentally conscientious chemical operations at every stage of the process.

- **Flare Destruction Efficiency R&D**: The Methane Mitigation subprogram also targets technology development for cases where gas flaring is unavoidable. Alternative uses for flared gas may prove technical infeasible or the payment of royalties may be economically acceptable to the operator, and routine natural gas flaring will still occur. For these situations, DOE will support the development of new ultra-high flare performance designs for the destruction of methane and all other environmentally harmful natural gas constituents present at well site flares. This effort includes design of the combustors and integrated multi-gas sensors and sensor arrays that ensure methane, carbon monoxide, and other gases that are intended to be destroyed by the flare are not being emitted due to suboptimal operation. These efforts include development of well site flare systems with advanced feedback controls that can retrofit existing air, steam, and fuel assisted flares and include continual monitoring and data processing algorithms to maintain optimal flare operation across extreme changes in environmental conditions and feed gas composition and flow. The development includes advancement of designs that ensure flame stability and new catalytic materials and systems for maintaining high conversion of unwanted emissions. Well site field validation of ultra-efficient flaring combustors with integrated performance monitoring, sensors, and control algorithms will ensure technologies developed under this effort can accelerate toward commercialization.
- **Technologies for Determining the Condition of UOW Boreholes Using Remote Sensing Technologies**: Effective characterization of the borehole and casing materials is an essential element of any effective P&A operation. Determining the condition of the borehole and casing provides information on damage, deformation, and potential communication points with reservoir fluids, including underground sources of drinking water. In the case of undocumented orphaned wells, developing and validating the use of non-invasive technologies for borehole assessment lessens the possibility of additional damage to the borehole or the loss of equipment that must be deployed in the subsurface for characterization purposes. Remote sensing approaches could include aerial survey equipment or surface deployable characterization tools that require a minimal surface footprint for effective borehole assessment.
- **Novel, Advanced Remediation Materials for UOW Boreholes in Various Conditions and with Minimal Surface Disturbance, including, but not limited to, Various Biofilm and Biochar Technologies**: As the number of wellbores requiring effective P&A increases, the need for low-cost materials for permanent plugging will also increase. Cementitious materials typically used for well plugging can be expensive and may not be effectively deployable in newly identified wellbores that are of variable geometries, diameters, or are damaged in a manner that cannot be effectively repaired prior to plugging. New materials that provide for the biochemical deposition of carbonate plugging minerals or other low-carbon sealing concepts will help accelerate the possibility that larger numbers of wellbores can

be permanently plugged and abandoned more quickly. Permanent P&A of UOW boreholes can also reduce communication with active oil and natural gas production operations within their area of influence.

- **Cost Effective Long-Term Well Monitoring Techniques and Technologies**: A variety of low-cost, autonomous monitoring solutions will be required to effectively identify and delineate potential impacts to air, water, and other sensitive receptors from UOWs both before and after P&A operations. These will need to include technologies that can improve measurement, estimation, and tracking techniques for gaseous emissions related to orphaned wells, including remote, real-time, autonomous, and continuous measurement applications, and methods that can leverage and integrate data-driven solutions to ensure accurate tracking of gaseous emissions related to orphaned wells as compared to other sources of emissions.
- **Approaches for Determining the Need for Novel P&A Techniques**: UOWs can be located in areas with minimal surface access, due to limited (or non-existent) surface roads, topography that limits existing equipment viability, overhead access limitations (forest canopy limitations), and other potential safety hazards. In order to facilitate future technology development, deployment, and validation, processes for determining when novel P&A techniques would be required, including discussions of cost, ease of installation, surface requirements, subsurface limitations, and additional training needs, will help accelerate additional future R&D in this space.

Based on findings from these projects, as well as the results of FECM monitoring of developing trends in oil and natural gas industry methane emissions regulations, industry reactions to those regulations, and voluntary industry efforts to monitor and minimize methane emissions, FECM will consider the need for additional solicitations for follow-on methane mitigation research.

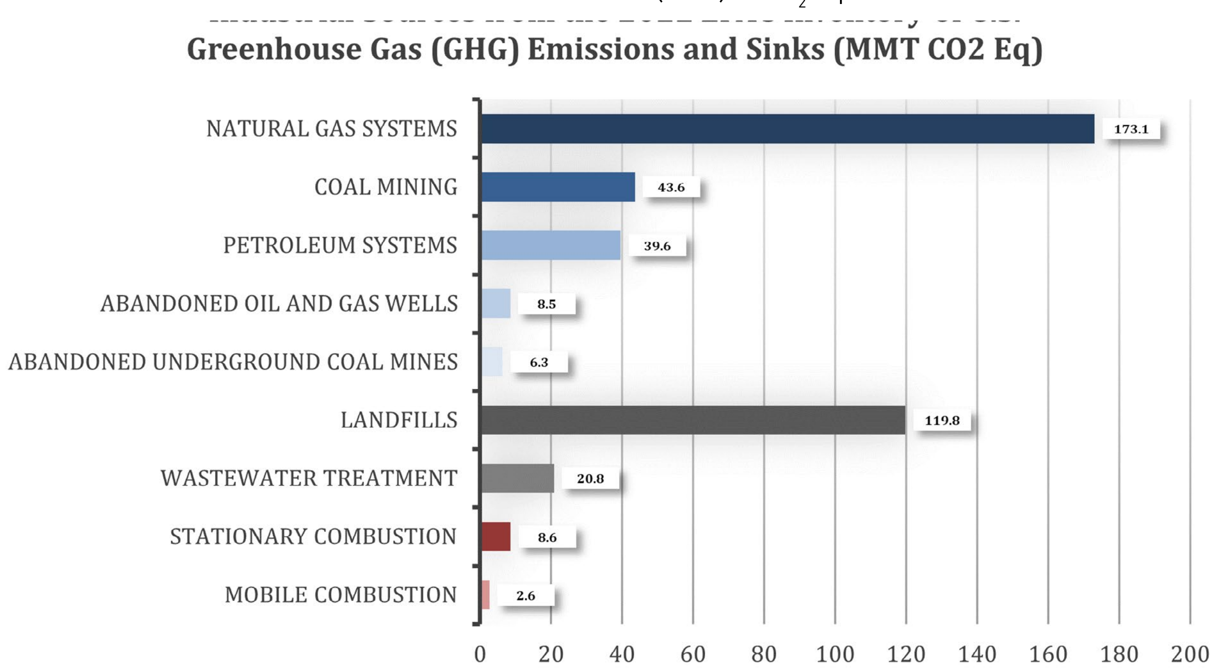
3. Future R&D Opportunities

While the previous sections outline DOE's plans for the various elements of the MMT Program over the 2025-2030 timeframe, there are also other areas where increased R&D is expected to be necessary post-2030. These areas are outlined below.

Quantifying and Mitigating Methane Leakage from Other Industrial Sources

There are opportunities to apply measurement, mitigation, and quantification technologies developed for the oil and natural gas supply chain to other industries. A subset of the emissions of methane that would be considered to be from industrial sources, rather than agriculture or biological, can be seen in Figure 7 based on the EPA's 2022 Inventory of U.S. Greenhouse Gas (GHG) Emissions and Sinks.

Figure 7. Methane emissions sources in million metric tons (MMT) of CO_2 Equivalent.



The methane losses across the industrial point sources related to oil and natural gas infrastructure and combustion operations are significant, and thus this area is a primary focus for the Methane Mitigation Technologies R&D as discussed earlier. However, the measurement, quantification, and mitigation technologies being developed by the program are not necessarily limited to oil and natural gas supply chain components. The characterization of the methane leakage and the mitigation strategies to eliminate leakage from oil and natural gas components can be adapted for other industrial sources such as coal mines, landfills, and wastewater treatment plants.

Abandoned mine methane (AMM) is a by-product of subsurface coal mining operations across several thousand abandoned coal mines in the United States. Of these, EPA has identified some 400 abandoned mines that are considered "gassy" and represent a significant source of methane emissions to the atmosphere.[19] The quantity and the emission rate of AMM may vary depending on the type of mine, the gas content of the mined coal seam, and the amount of gas sourced from strata and coal beds in overlying and underlying formations affected by mining operations. As mines mature and coal seams are mined out, mines are closed and eventually abandoned. Mine portals, vent shafts, and other small footprint infrastructure components that may not have been adequately documented and characterized by the EPA and other regulatory bodies. Shafts or portals are often filled with gravel and capped with concrete seals; vent pipes and boreholes are often plugged in a similar manner to oil and gas wells.[20] When active mining stops, the mine's methane gas production decreases but does not stop completely. Following an initial decline, abandoned mines can liberate methane at a near-steady rate over an extended period. The gas can migrate up through a variety of conduits, particularly if they have not been sealed adequately. It can also migrate to the surface through natural fractures and fissures in the strata overlying the coal mine, leading to diffuse emissions. One factor affecting this process is flooding: when a mine floods after groundwater or surface water intrudes into the void, that mine typically produces gas for only a few years.[21] There are also challenges to the utilization of methane from coal mines related to obtaining ownership rights to operate methane capture systems on abandoned mines and obtaining the rights to produce and sell the methane as a product for active and abandoned mines.[22] Prior to beginning mining operations, degasification through intentionally drilled boreholes can remove the methane, but an onsite use or a market need, along with access to adequate infrastructure, must be established. Removal of coal mine methane faces economic challenges as well due to the increased equipment and operational costs for mining companies. The methane in coal mines can also escape from areas other than the intended outlets, creating challenges for collection systems.[23] The methane mitigation technologies developed as part of the MMT Program related to modular gas collection, processing, and conversion, as well as innovative transport options, can likely impact the beneficial use of methane from coal mines as well.

Methane created in landfills is typically high enough for it to be used to create electricity or provide heat as a medium British Thermal Unit (BTU) fuel after multiple gas treatment steps to remove impurities. If pipeline quality, high BTU methane is desired from landfill gas emissions, additional advanced gas separation treatment is generally required to remove CO_2 and other gases before compression and delivery.[24] The primary challenges associated with capturing landfill gas at the source are associated with the required preparation of the landfill site. This includes engineering manageable slopes, depositing multiple ground covers to avoid erosion and methane leaks, and the drilling of multiple wells in an overlapping perforation pattern to extract the methane being produced by the decomposition of the organic portions of the waste material. This site preparation prevents additional municipal waste that can be deposited in the area that is now prepared for methane capture. Additionally, landfills have challenges associated with removing the methane from the areas of the landfill that are still actively accepting waste that will continue to release methane into the air until the site is decommissioned and the required site preparation and methane capture equipment can be installed.[25] The advanced sensors, monitoring systems, and lower pressure gas processing and separation technologies that are being developed of the MMT Program can likely be extended to have a beneficial impact in landfill gas operations.

Wastewater treatment plants that use anaerobic digesters make up approximately 10% of the total number of treatment plants in operation but treat about 55% of the wastewater in the United States. The digesters contain microbes capable of breaking down sludge and solid waste into biogas with enough methane to power other parts of the treatment process. The challenge with these sources is predominately related to undetected leaks and inefficient handling equipment that allows significant amounts of methane to escape to the atmosphere, particularly when operating at high pressure. Additionally, the production rate of methane from these sources can be a challenge, as it is not constant throughout the day.[26] The technologies developed as part of the MMT Program that optimize the use and processing of raw casing head gas at various flow rates and compositions, as well as the advance methane quantification and detection systems, can likely have a positive impact by expanding into wastewater biogas operations.

The MMT Program will seek to better characterize and quantify methane emissions in a manner that has the potential to expand into all industrial sources looking to minimize methane losses. The development and validation of these technologies within the oil and natural gas industry will facilitate further optimization of other industries, whether new components and retrofits, improved processing operations, or modular methane conversion technologies.

Safer, Resilient Natural Gas Storage

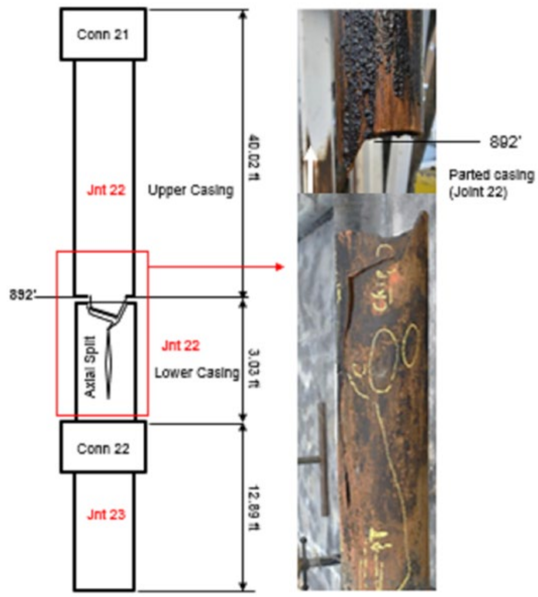
Most existing natural gas storage in the United States is found in depleted natural gas or oil reservoirs that are close to major end-users. Conversion of a depleted natural gas or oil reservoir from production operations to storage takes advantage of existing wells, gathering systems, and pipeline connections. Such reservoirs are the most commonly used underground storage sites because of their availability and stable condition.

In some areas, natural saline aquifers have been converted to natural gas storage reservoirs. An aquifer is suitable for gas storage if the brine-bearing sedimentary rock formation is overlaid with an impermeable cap rock. Although the geology of aquifers is similar to depleted production fields, their use for natural gas storage usually requires additional cushion gas and additional reservoir pressure management to ensure safe injection and withdrawal operations. Deliverability rates may be enhanced by the presence of an active water drive, which supports the reservoir pressure through the injection and production cycles.

Salt caverns provide very high withdrawal and injection rates relative to their working gas capacity. Most salt cavern storage facilities have been developed in salt dome formations located in the Gulf Coast states. Salt caverns have also been created (by a process called leaching) in bedded salt formations in Northeastern, Midwestern, and Southwestern states. Cavern construction is more costly than depleted reservoir conversions when measured on the basis of dollars per thousand cubic feet of working gas capacity, but the ability to perform several withdrawal and injection cycles each year reduces the per-unit cost of each thousand cubic feet of gas injected and withdrawn.[27]

As new regulatory, safety, and monitoring requirements emerge as a result of the Aliso Canyon well failure,[28] the MMT Program will investigate the potential for next generation wellbore materials for increased resiliency under severe subsurface conditions (e.g., long-term microbial exposure, see Figure 8), enhanced remote sensing concepts for large-scale, high-resolution aerial monitoring of natural gas storage fields (including wellbores and surface components), and the characterization of depleted tight natural gas reservoirs for additional subsurface storage capacity.

Figure 8. Image of parted casing from the SS-25 well at Aliso Canyon. One reason for the failure of the casing material was long-term exposure to microbes that degraded the integrity of the casing.

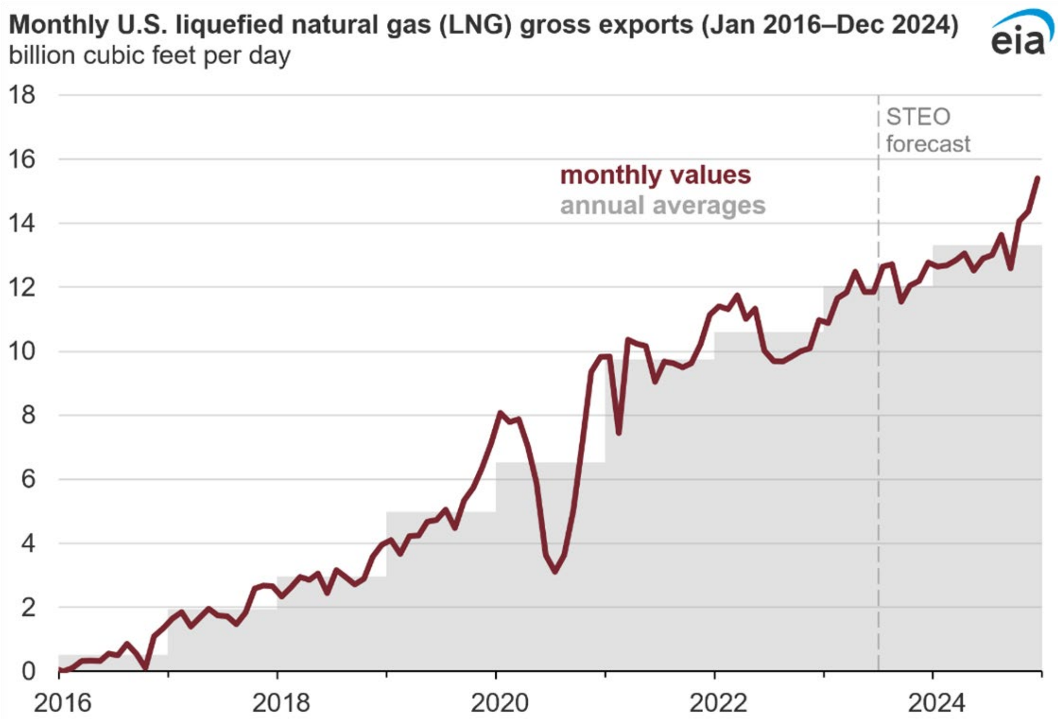


Liquified Natural Gas—Liquefaction and Transport Emissions Quantification

Liquified natural gas (LNG) is natural gas that is cooled to become a liquid form to enable safe and reliable transportation to market areas that pipelines cannot reach. When a quantity of natural gas is converted to LNG, it is 600 times smaller in volume than in its gaseous state.[29] The liquefaction process removes impurities from the natural gas stream such as dust, acid gases, helium, water, and heavier hydrocarbons. The U.S. has dramatically increased the volume of LNG it exports over the last 5 to 8 years and in 2022 exported 3,865.64 billion cubic feet of natural gas as LNG (see Figure 9).

With exports expected to increase as new U.S. LNG export capacity comes online in the upcoming years, the ability to effectively liquefy and quantify emissions from LNG transportation will be crucial.[30] As LNG exports become more prevalent and environmental issues, such as emissions, are more closely scrutinized, there will likely be a growing market for LNG that is certified as having been produced with minimal emissions under Environmental, Social, and Governance (commonly known as ESG) practices. Therefore, validating the emissions profile of LNG production, storage, and transportation will be vital for the U.S. to continue to lead in supplying LNG to the world.

Figure 9. U.S. LNG imports and exports from 1985 to 2022



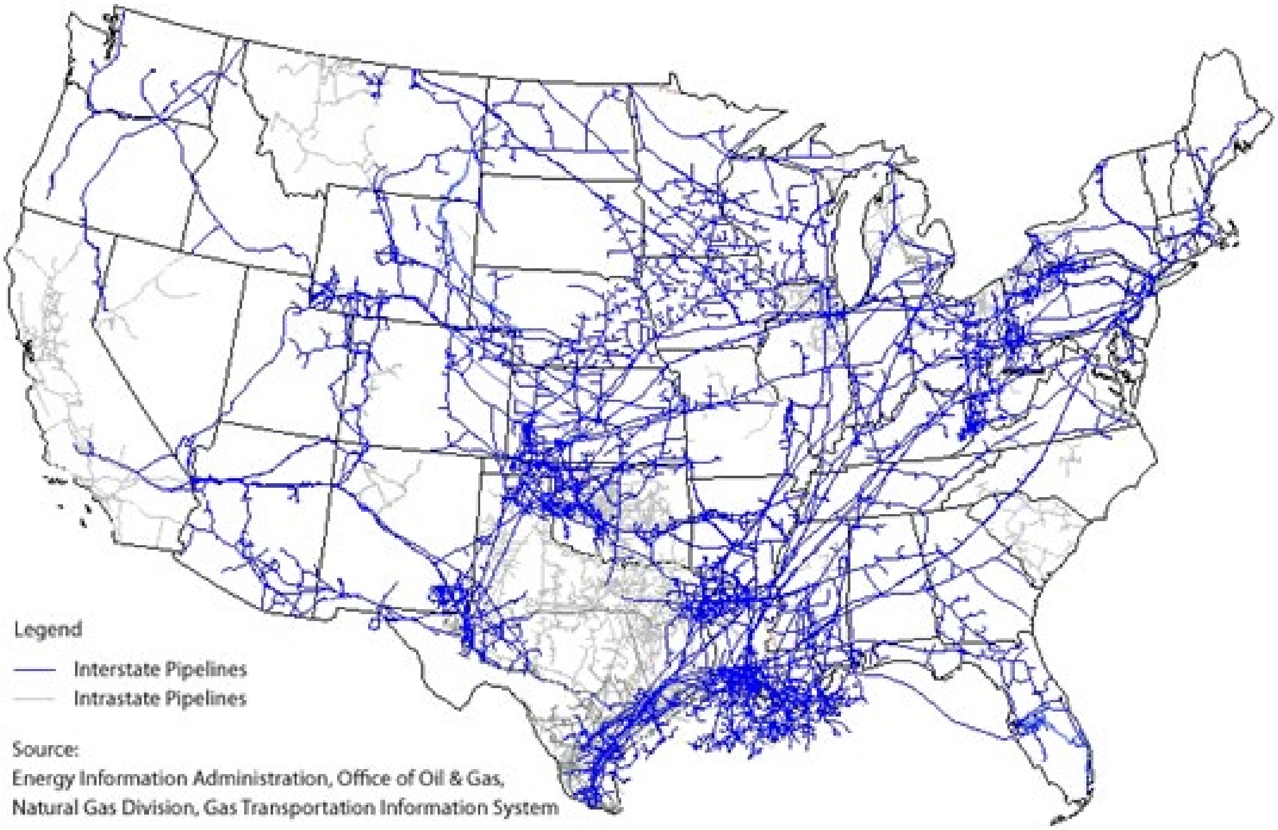
Blended Natural Gas

The U.S. has a vast natural gas pipeline system which can transport and deliver natural gas to and from almost any location in the lower 48 states (Figure 10). The transportation system consists of over 305,000 miles of transmission pipelines and 2.2 million miles of distribution pipelines. Blended natural gas is a mixture of natural gas and other fuels, such as hydrogen. While pipeline transmission of hydrogen can present problems with leaks and metal embrittlement, it appears that blended mixtures of methane and hydrogen gas can safely contain up to 20% hydrogen.[31]

DOE is supporting the HyBlend project involving National Renewable Energy Laboratory (NREL) and five other DOE labs, in which different hydrogen blends are being tested on different pipeline materials. The goal of the research is to determine the true impacts of hydrogen embrittlement on existing or new transmission infrastructure, as well as the economics and practicality of upgrading existing natural gas infrastructure to transport a hydrogen and natural gas blended gas stream.

Challenges regarding blended natural gas streams increase when hydrogen exceeds 20% of the total volume. Because hydrogen is three times less energy dense than methane, as the ratio of hydrogen rises, the volume of energy being delivered through pipelines decreases. Additionally, because hydrogen will combust across a wider range of air concentrations than methane, making combustion more difficult to control, when hydrogen volumes exceed 25% equipment must be made intrinsically safe, or explosion proof.[32]

Figure 10. U.S. National Gas Pipeline Network (EIA)



The MMT Program will continue to support R&D to determine the viability of utilizing or retrofitting existing natural gas pipelines to transport natural gas and hydrogen blends. Simultaneously, the MMT Program will expand its R&D program to investigate requirements to support blended natural gas stream transmission throughout the U.S. by developing advanced materials, coatings, gas separation, and leak detection technologies.

4. Collaboration

The MMT Program collaborates with technology developers, academic scientists, and industry stakeholders to ensure that the research topics are well aligned with Administration goals, Congressional priorities, and the needs of operators and service companies looking to eliminate methane emissions from their operations. In addition, the MMT Program supports DOE and Administration objectives through a variety of interagency collaborations, including the following:

Measurement, Monitoring, Reporting, And Verification System

A comprehensive, nation-wide MMRV system combines U.S. capabilities and expertise in greenhouse gas (GHG) emissions and removal measurements, analysis, and modeling across numerous U.S. agencies, the private sector, and academia. The system concept is proposed to be operational, relying on two primary emission and removal quantification components: atmospheric (top-down) observations and models, and facility-scale (bottom-up) measurements and models. The bottom-up component is based on EPA's GHGI, composed of measurements and models describing emissions and removals at the facility level. Atmospheric methods simultaneously sensitive to all emissions and removals to and from the atmosphere, combined with the bottom-up component, gives the system cross-component validation capability (though top-down methods are currently limited in spatial coverage). Current bottom-up capabilities, having broad coverage of emissions and removals domestically, coupled with top-down methods ranging from surface networks to satellite observational data combine to ultimately give the system full landmass coverage domestically with potential for global applications. In addition to DOE, top-down elements of the research effort are mainly those of the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), the National Institute of Standards and Technology (NIST), and some private sector contributions.

DOE has selected seven projects focused on IM^{3}CP design awarded in 2023. The University of Texas at Austin, University of Oklahoma, Gas Technology Institute, Sonoma Technology, ABB, Inc., Pacific Northwest National Laboratory, and Piedmont Natural Gas will each lead teams of researchers in the development of comprehensive engineering, design, deployment, and operation plans. The projects are designed to enable a fully integrated, continuous methane monitoring and reporting platform that can accelerate the creation of a "leak-tight" natural gas production chain. DOE will evaluate all the submitted plans before selecting the best past forward for implementation.

It is anticipated that several of the projects focused on designing potential frameworks for an IM^{3}CP will deliver early work products that highlight key data gaps and technology challenges. Once these designs are completed, FY25 funds may be directed towards initiation of efforts to build and test prototypes.

RESPONSIBLY SOURCED GAS (RSG)

There is a burgeoning industry that provides methane emissions quantification and certification, each using its own definitions and processes, and many U.S. natural gas producers have already begun working with them to certify their production. In late 2022, DOE leadership hosted a workshop to bring together domestic and international stakeholders from industry, academia, and RSG service providers to facilitate discussions related to the development of standards for responsibly sourced natural gas. Discussions also focused on identifying how DOE and other government agencies can be mutually supportive of these efforts in the realm of technology development and validation, along with continued collaboration for accelerated deployment of RSG concepts across the natural gas value chain.

As the leading government sponsor of methane emissions quantification and mitigation research, DOE can also ensure that its R&D efforts focus on technologies that enable companies to participate in a market for responsibly sourced natural gas. Further, as the leading voice for the U.S. energy sector in international conversations, DOE can support domestic industry's efforts to meet international customers' expectations.

References

[1] The National Petroleum Council, Dynamic Delivery—America's Evolving Oil & Natural Gas Transportation Infrastructure. https://dynamicdelivery.npc.org

[2] The National Academies Press, *Greenhouse Gas Emissions Information for Decision Making: A Framework Going Forward*. https://nap.nationalacademies.org/catalog/26641/greenhouse-gas-emissions-information-for-decision-making-a-framework-going

[3] U.S. Environmental Protection Agency, *Estimates of Methane Emissions by Segment in the United States*. https://www.epa.gov/natural-gas-star-program/estimates-methane-emissions-segment-united-states

[4] National Academy of Sciences, 2018, *Improving Characterization of Anthropogenic Methane Sources in the United States*. https://nap.nationalacademies.org/catalog/24987/improving-characterization-of-anthropogenic-methane-emissions-in-the-united-states

[5] U.S. Energy Information Administration, *Natural gas venting and flaring increased in North Dakota and Texas in 2018*, December 2019. https://www.eia.gov/todayinenergy/detail.php?id=42195#:~:text=In%202018%2C%20the%20percentage%20of,vented%20and%20flared%20natural%20gas

[6] U.S. Department of Energy, *Natural Gas Flaring and Venting: State and Federal Regulatory Overview, Trends, and Impacts,* June 2019. https://www.energy.gov/sites/prod/files/2019/08/f65/Natural%20Gas%20Flaring%20and%20Venting%20Report.pdf

[7] U.S. Energy Information Administration, *U.S. Natural Gas Vented and Flared*, January 31, 2023. https://www.eia.gov/dnav/ng/hist/n9040us2a.htm

[8] Howard Center investigation examines how regulators are unaware of how much greenhouse gases are released by oil and gas companies. (2023). Retrieved from https://cronkite.asu.edu/news/2022/howard-center-investigation-examines-how-regulators-are-unaware-of-greenhouse-gas-levels-released-by-oil-and-gas-companies/

[9] New study quantifies natural gas wasted on U.S. public and Tribal Lands. Environmental Defense Fund. (2023, January 26). https://www.edf.org/media/new-study-quantifies-natural-gas-wasted-us-public-and-tribal-lands#:~:text=It%20is%20time%20for%20the,gas%20lost%20through%20flaring%20alone.

[10] Plant, Genevieve, et al. *Inefficient and Unlit Natural Gas Flares Both Emit Large Quantities of Methane*. Science, vol. 377, no. 6614, 2022, pp. 1566–1571. https://doi.org/10.1126/science.abq0385

[11] Pennsylvania Department of Environmental Protection, *Abandoned and Orphaned Oil and Gas Wells and the Well Plugging Program Factsheet*. https://www.dep.pa.gov/Business/Energy/OilandGasPrograms/OilandGasMgmt/Documents/8000-FS-DEP1670.pdf?Mobile=1&Source=%2FBusiness%2FEnergy%2FOilandGasPrograms%2FOilandGasMgmt%2F_layouts%2Fmobile%2Fview.aspx%3FList%3D064370e5-1e17-4182-bb2a-3f9b5c88dba4%26View%3De28f393a-8f5e-4d78-8244-3d57fa89de47%26CurrentPage%3D1

[12] Texas Railroad Commission, Orphan Wells with Delinquent P-5 Greater than 12 Months.

[13] Interstate Oil and Gas Compact Commission (IOGCC), *Idle and Orphan Oil and Gas Wells: State and Provincial Regulatory Strategies*, 2021. https://oklahoma.gov/content/dam/ok/en/iogcc/documents/publications/iogcc_idle_and_orphan_wells_2021_final_web.pdf

[14] ibid

[15] NRDC, *Millions of Leaky and Abandoned Oil and Gas Wells are Threatening Lives and the Climate*, July 26, 2021. https://www.nrdc.org/stories/millions-leaky-and-abandoned-oil-and-gas-wells-are-threatening-lives-and-climate

[16] U.S. Department of Energy, *Project Selections for FOA 2616: Innovative Methane Measurement, Monitoring and Mitigation Technologies*. https://www.energy.gov/fecm/project-selections-foa-2616-innovative-methane-measurement-monitoring-and-mitigation

[17] U.S. Department of Energy, Funding Opportunity Announcement (FOA) Number: DE-FOA-0003017, *Innovative Technologies to Eliminate Flaring from Oil and Natural Gas Production*. https://www.fedconnect.net/FedConnect/default.aspx?ReturnUrl=%2ffedconnect%3fdoc%3dDE-FOA-0003017%26agency%3dDOE&doc=DE-FOA-0003017&agency=DOE

[18] U.S. Department of Energy, Project Selections for FOA 3017: *Innovative Technologies to Eliminate Flaring from Oil and Natural Gas Production*. https://www.energy.gov/fecm/project-selections-foa-3017-innovative-technologies-eliminate-flaring-oil-and-natural-gas

[19] ibid

[20] U.S. Geological Survey (USGS), Assessment of coal mine methane (CMM) and abandoned mine methane (AMM) resource potential of longwall mine panels: example from Northern Appalachian Basin, USA. https://pubs.usgs.gov/publication/70203460

[21] U.S. Environmental Protection Agency, *Abandoned Coal Mine Methane Opportunities Database*. https://www.epa.gov/sites/default/files/2016-03/documents/amm_opportunities_database.pdf

[22] *Infrastructure Podcast: Tackling Methane Emissions from Abandoned and Active Coal Mines*. World Bank. Accessed June 11, 2024. https://www.worldbank.org/en/news/podcast/2022/03/02/tell-me-how-tackling-methane-emissions-from-abandoned-and-active-coal-mines.

[23] *Strategies to Reduce Emissions from Coal Supply – Global Methane Tracker 2023 – Analysis*. International Energy Agency (IEA). Accessed July 3, 2024. https://www.iea.org/reports/global-methane-tracker-2023/strategies-to-reduce-emissions-from-coal-supply

[24] U.S. Environmental Protection Agency, *Basic Information about Landfill Gas*. https://www.epa.gov/lmop/basic-information-about-landfill-gas

[25] Kashyap, R.K., Chugh, P., Nandakumar, T. *Opportunities & Challenges in Capturing Landfill Gas from an Active and Un-Scientifically Managed Land Fill Site – a Case Study*. Procedia Environmental Sciences 35 (2016): 348–67. https://doi.org/10.1016/j.proenv.2016.07.015

[26] Moore, D., Li, N., Wendt, L., Castañeda, S., et al. *Underestimation of Sector-Wide Methane Emissions from United States Wastewater Treatment*. Environmental Science & Technology 57, no. 10 (2023): 4082–90. https://doi.org/10.1021/acs.est.2c05373.

[27] U.S. Energy Information Administration, *The Basics of Underground Natural Gas Storage*. https://www.eia.gov/naturalgas/storage/basics/

[28] California Public Utilities Commission, Aliso Canyon Well Failure. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiJtOG__NWJAxWlElkFHSIxMcAQFnoECAoQAQ&url=https%3A%2F%2Fwww.cpuc.ca.gov%2Fregulatory-services%2Fsafety%2Fgas-safety-and-reliability-branch%2Faliso-canyon-well-failure&usg=AOvVaw1sYULK04fanqOS9WpfGeaC&opi=89978449

[29] U.S. Department of Energy, FECM. *Liquefied Natural Gas (LNG)*. https://www.energy.gov/fecm/liquefied-natural-gas-lng

[30] U.S. Energy Information Administration, Natural Gas Explained. https://www.eia.gov/energyexplained/natural-gas/liquefied-natural-gas.php#:~:text=Liquefied%20natural%20gas%20(LNG)%20is,on%20ships%20and%20on%20trucks

[31] U.S. Department of Energy, Alternative Fuels Data Center, *Natural Gas Fuel Basics*. https://afdc.energy.gov/fuels/natural-gas-basics

[32] Greentech Media, *Green Hydrogen in Natural Gas Pipelines: Decarbonization Solution or Pipe Dream?* https://www.greentechmedia.com/articles/read/green-hydrogen-in-natural-gas-pipelines-decarbonization-solution-or-pipe-dream

U.S. Department of ENERGY